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Emissions of monoterpene from tropical Indian plant species and assessment of VOC emission from the forest of Haryana state

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ABSTRACT

Monoterpene emission samples of 50 Indian plant species were collected using a dynamic flow–through enclosure chamber technique and concentrations were determined with the help of GC–FID/MS. Monoterpene emission rates of different plant species ranged from negligible to 16.9 μg g^{-1} h^{-1}. Thirty four of the screened fifty plant species, were found to be monoterpene emitters. Volatile organic compound (VOC) emission capacity of predominantly plantation forest of Haryana was also estimated, which was found to be 20.9 mg C m^{-2} h^{-1}. Individual plant species area averaged VOC emission capacity ranged from negligible to 12.0 mg C m^{-2} h^{-1}. *Dalbergia sisoo* and *Eucalyptus globulus*, were found to contribute approximately 82% of the total VOC emission capacity.

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1. Introduction

Numerous volatile organic compounds (VOCs) are emitted by plants into the atmosphere. It is estimated that vegetation contributes about 90% of the total biogenic VOC emissions (Guenther et al., 1995). In the atmosphere, VOCs quickly react with hydroxyl radical, ozone, and nitrate radical leading to the formation of carbon monoxide, organic acids, and secondary aerosols (Fehsenfeld et al., 1992; Atkinson, 2000). Isoprene and monoterpene are the most abundant VOCs emitted from the plants, which are estimated to account 44% and 11%, respectively to the global biogenic VOC budget of 1 150 Tg C yr^{-1} (Guenther et al., 1995). In India, numerous planting programmes such as afforestation, social forestry, urban green belt development and avenue plantations have been implemented since 1979 in order to increase vegetation cover and meet the increasing demand of raw material for forest based industries. Plantation area has been expanding at a fast pace and likely to further increase in view of government thrust on increasing vegetation cover (SFR, 2005). Plantation forests have occupied more than 33 260 km^2 of the total forested area of 637 293 km^2 of India. This is leading to drastic transformation of many landscapes throughout the country in terms of species composition, foliar density, successional stage and land use pattern. To assess possible chemical consequences of land cover changes, it is important to ascertain VOC emission patterns of landscapes undergoing intense transformation, especially when the changes are dominated by replacement of natural mixed forests by monospecific forest plantations. Common Indian plant species have been examined for isoprene emissions (Varshney and Singh, 2003; Padhy and Varshney, 2005; Singh et al., 2007; Singh et al., 2008), but measurement studies on monoterpene emissions are altogether lacking. Besides, biogenic VOC emission estimates for the country forests have not been attempted so far. Current global VOC emission estimates are derived from assumptions on ecosystem scale VOC emissions. In order to improve reliability and accuracy of global VOC estimates, it is important to prepare VOC estimates for different ecosystems on the basis of measurement studies on the plant species of the region. This study was undertaken with the following objectives: (i) to measure monoterpene emission rates of common Indian plant species and (ii) to prepare VOC emission estimates for the forest of Haryana state of India, which represents one of the most drastically transformed forest landscapes of India.

2. Experimental

2.1. Study site descriptions

Haryana is one of the states of India, situated in close proximity of national capital of Delhi. It is located between 74˚–78˚ east longitude and 27˚– 31˚ north longitudes and lies within the subtropical belt. It has a maximum temperature of 45 ˚C in summer and minimum 5 ˚C in winter with an annual mean temperature of approximately 25 ˚C. Haryana receives an average annual rainfall of 75 cm, 80% of which is received during June to August. The geographical area of the Haryana state is 44 000 km^2, out of which 1 500 km^2 (3.39%) is forest area (Sapra, 2000). The forest of Haryana is basically a sub–tropical dry deciduous plantation forest. Earlier, most of the natural forests of the state were cleared for agricultural purposes. Since 1967 numerous

plantation programmes have been implemented in order to raise vegetation cover and to revive the degraded forests. The area of plantation forest is about 5 times of natural forest area of the state (Anon, 1999). The forest of Haryana state consists of 21.9% *Acacia nilotica*, 21.8% *Eucalyptus globulas*, 15.1% *Prosopis juliflora*, 12.1% *Dalbergia sissoo*, 3.4% *Azadirachta indica*, 3% *Acacia catechu*, 2.4% *Mangifera indica*, 2.5% *Populus species*, 2.2% *Morus alba*, 2.4% *Acacia tortilis*, 1.9% *Zizyphus species*, 1.1% *Eugenia jambolanum* and 7.2% miscellaneous species (Sapra, 2000). The miscellaneous species comprises of *Ficus species, Pongamia pinnata, Salmalia malabarica, Albizzia lebbeck, Terminalia, Kigelia pinnata* and *Pithecollobium dulce*.

2.2. Emission measurements

Fifty commonly growing plant species of India were selected for the study. About eight year old saplings of the plant species were purchased from local nurseries and maintained in the earthen pots containing fertile garden soil mixed with organic manure in the ecological garden. Plants were watered at regular intervals. A dynamic flow through enclosure system as employed previously by Street et al. (1996) was used for emission measurements. The enclosure chamber was constructed from 0.2 mm transparent polycorbonate sheet measuring approximately 38×39×46 cm. The enclosure chamber was equipped with a fan and inlet and outlet ports suitable for introduction of matrix air and withdrawal of analytical samples respectively. The enclosure was carefully fitted around the stem of plant sapling and sealed properly with the help of Teflon tape. Air was passed through enclosure chamber at a rate of 20 L min^{-1} and this flow was maintained for 20 minutes prior to sampling. Samplings were carried out for 10 minutes as described by Winer et al. (1989) at a rate of 0.10 L min^{-1} from enclosure on to Tenax TA (200 mg)/ carbosieve II (100 mg) solid adsorbent (Obtained from Supelco Inc. Bellefonte, PA). The packed Tenax TA/carbosieve tubes were preconditioned by heating at 300 ˚C for about 24 hours with continuous purge of nitrogen. After sampling, Tenax tubes were sealed with Teflon ferrules and stored at 4 ˚C and the samples were analysed within 30 minutes. Three plants of individual plant species were sampled during daylight hours between 9.0 am to 5.30 pm. Temperature and photosynthetically active radiation (PAR) were measured both inside and outside the chamber with the help of thermometer and Li Cor Quantum sensor, LI–185 (Li–Cor biosciences, Lincoln, NE, U.S.A) respectively. Inlet and outlet airflow rates of enclosure chamber were measured by calibrated rotameters.

A Perkin Elmer gas chromatograph (Perkin and Elmer ATD 400, Perkin Elmer, UK) with a fused silica capillary column (length: 30 m, id: 0.53 mm, bonded phase BP–50 I, Alltech Associates, Dearfield, IL, USA) connected with flame ionization detector (FID) was used for the analysis of most of the samples. For each species, representative samples were also analysed using GC–MS (Perkin and Elmer ATD 400, Perkin Elmer, UK) for optimum peak identification. Compounds were desorbed at 250 ˚C for 8 minutes from the Tenax TA/carbosieve sampling tube by a thermal desorber injection system connected the GC. The initial oven temperature was maintained at 40 ˚C for 5 minutes, then, increased to 150 ˚C at a rate of 5 ˚C min^{-1} for 5 minutes thereafter temperature increased at a rate of 15 ˚C up to 250 ˚C and maintained for 10 minutes. N_2 was used as the carrier gas and the flow rate was maintained at 8 mL min^{-1}. The injection temperature was 230 ˚C and detector temperature was 250 ˚C. Monoterpenes in the samples were determined with the help of standard calibration plots prepared from the liquid chemical standard obtained from Fluka/Sigma–Aldrich, USA. Gas–phase liquid chemical standards of seven monoterpenes, (i.e., α – pinene, *β*–pinene, *d*–limonene, myrcene, sabinene, camphene and carene) were prepared by serial dilution in round flasks fitted with screw cap syringe sampling ports. A weekly calibration was performed for monoterpenes. The four different concentrations of monoterpenes (i.e. 10, 50, 100 and 200 ppb in 100 cm^3 of air) were drawn into a 100 cm^3 gas tight syringe (Hamilton co.) and injected in to the Tenax end of the Tenax TA/carbosieve tubes (Nucon Engineer, Okhala, New Delhi) and tubes were placed directly into the injection port and desorbed with the Tenax end directly above the column. To prevent any loss of the standards, less than 4 seconds elapsed between placing the sample tube into the injection port and placement of the cover and less than 40 seconds usually elapsed between the placement of the insert into the injection port and the start of the run. Response factors were generated by dividing the standard concentration by the peak area for isoprene and seven different monoterpenes at that concentration and multiplying by the volume of standard taken (in liters). Response factors were used for the calculation of monoterpene concentrations from the observed peak areas. Some monoterpenes (other than seven monoterpenes for which standard was available) present in the samples could not be identified. Quantitative determinations of these monoterpenes were carried out by using *α*–pinene standard calibration plot. The precision and accuracy of the GC/FID system were about 4% as determined by repeated measurements of the standard gas. After the emission flux measurements were completed, the entire branch, which has been enclosed in the chamber, was harvested, and the leaves were stripped off the stems and then dried in an oven at 70 ˚C to a constant weight in order to obtain the dry mass of each plant.

Measured monoterpene emission rates were normalised to temperature of 30 ˚C, using the algorithm proposed by Guenther et al. (1993):

$$M = M_s \exp [\beta(T–T_s)] \quad (1)$$

where, M_s is the normalised monoterpene emission rate (μg g^{-1} h^{-1}), M is non–normalised monoterpene emission rate, β is an empirically determined coefficient (0.09 K^{-1}), T is the temperature (in Kelvin) and T_s is the standard temperature (303 K).

The temperature of well–mixed air inside the enclosure was used to normalise the emission rates because the leaf temperature was not measured in this study.

2.3. Species emission and landscape emission capacities

VOC emission estimate for the forest of Haryana state was determined using the method by Guenther et al. (1995). The area average emission capacity (F, mg m^{-2} h^{-1}) was calculated as:

$$F = \varepsilon D \gamma \quad (2)$$

where, ε is the area average emission capacity (mg m^{-2} h^{-1}) at a PAR flux of 1 000 mol m^{-2} s^{-1} and temperature 30 ˚C, *D* is foliar density (g m^{-2}), and γ is a non dimensional activity adjustment factor that accounts for the influence of PAR and leaf temperature conditions. The influence of light and temperature on VOC emission is estimated using the method by Guenther et al. (1993):

$$\gamma = C_L \times C_T \quad (3)$$

The scaling factors C_L and C_T are defined by the functions:

$$C_L = \alpha \times C_{L1} \times L \times [1+ \alpha^2 + L^2]^{-1/2} \quad (3a)$$

where, L is the PAR (μ mol m^{-2} s^{-1}), C_{L1} is an empirical coefficient (1.067) and α is an empirical coefficient (0.0027).

Table 1. *Monoteropene emissions (normalised to 30°C) from fifty seven Indian plant species*

Plant Species	Temp. (°C)	Emission	E.R. ($\mu g\ g^{-1}h^{-1}$)	T.E.R. ($\mu g\ g^{-1}h^{-1}$)	α-P (%)
Anacardiaceae					
Mangifera indica	27	β-P	7.0	16.9 ± 6.8	NIL
		Lim	9.0		
		Car	0.5		
		Cam	0.3		
		Oth	0.1		
Spondias pinnata	25	Oth	2.5	2.5 ± 1.9	NIL
Annona squamosa	34	NED	NED	NED	NIL
Apocynaceae					
Alstonia scholaris	40	NED	NED	NED	NIL
Bignoniaceae					
Haplophragma adenophylam	25	Oth	0.2	0.2 ± 0.2	NIL
Kigelia pinnata	39	α-P	0.3	1.26 ± 0.8	23.8
		β-P	0.5		
		Sab	1.18		
Bombacaceae					
Ceiba petendra	42	α-P	3.3	2.7 ± 5.5	25.9
		Sab	2.2		
		Myr	3.0		
		Oth	4.2		
Chorisia speciosa	37	α-P	0.8	2.2 ± 1.1	36.3
		β-P	0.2		
		Lim	1.2		
Salmalia malabarica	35	α-P	0.8	2.9 ± 1.7	27.5
		β-P	0.4		
		Lim	1.3		
		Myr.	0.3		
		Oth	0.1		
Caesalpiniaceae					
Bauhinia variegate	37	Sab.	1.1	1.6 ± 1.4	NIL
		Oth	0.5		
Bauhinia tomentosa	33	Oth	0.1	0.1	NIL
Cassia fistula	27	α-P	0.43	0.58 ± 0.4	72.8
		Oth	0.15		
Casia siamea	25	Oth	0.4	0.40 ± 0.2	NIL
Casia renigera	27	Oth	NIL	NIL	NIL
Emblica officinalis	34	NED	NED	NED	NIL
Delonix regia	26	α-P	0.28	0.98 ± 0.7	28.5
		Oth	0.7		
Combretaceae					
Terminalia arjuna	34	Sab.	0.03	0.08 ± 0.06	NIL
		Myr.	0.02		
		Oth	0.03		
Terminalia belirica	35	β-P	0.13	1.46 ± 1.1	NIL
		Sab.	1.24		
		Car.	0.09		
Fabaceae					
Butea monosperma	40	NED	NED	NED	NIL
Dalbergia sissoo	35	NED	NED	NED	NIL
Pongamia pinnata	30	α-P	0.07	2.32 ± 0.8	3
		Lim	0.05		
		Oth	2.2		

Table 1. *Continued*

Plant Species	Temp. (°C)	Emission	E.R. ($\mu g\ g^{-1}h^{-1}$)	T.E.R. ($\mu g\ g^{-1}h^{-1}$)	α-P (%)
Lauraceae					
Cinnamomum camphora	23	Oth	0.03	0.03 ± 0.02	NIL
Cinnamomum acerifolium	35	NIL	NIL	NIL	NIL
Meliaceae					
Azadirachta indica	40	β-P	0.15	2.43 ± 1.4	NIL
		Lim.	0.38		
		Cam.	0.9		
		Oth	1.0		
Cedrela toona	30	β-P	0.5	1.75 ± 1.1	NIL
		Cam.	0.3		
		Sab.	0.2		
		Lim	0.75		
Chukrasia tabularis	33	Oth	0.75	0.75 ± 0.4	NIL
Melia azedarach	38	Oth	0.51	0.51 ± 0.36	
Mimosaceae					
Acacia Arabica	37	NED	NED	NED	NIL
Acacia farnesiana	34	NED	NED	NED	NIL
Albizzia lebbeck	36	β-P	2.0	2.15 ± 1.6	NIL
		Oth	0.15		
Albizzia odoratissima	37	β-P	0.75	1.16 ± 1	NIL
		Car.	0.1		
		Myr.	0.25		
		Oth	0.15		
Pithecellobium dulce	33	α-P	0.2	0.47 ± 0.28	42
		Myr.	0.1		
		Oth	0.17		
Moraceae					
Ficus benghalensis	34	β-P	2.5	2.37 ± 0.92	NIL
		Sab.	0.31		
		Oth	0.1		
Ficus elastica	32	Oth	0.35	0.35 ± 0.25	NIL
Ficus glomerata	33	β-P	0.38	0.89 ± 0.33	NIL
		Sab.	0.30		
		Oth	0.21		
Ficus infectoria	32	Sab.	1.1	1.6 ± 0.9	NIL
		Oth	0.5		
Morus alba	36	α-P	1.3	11.3 ± 8.2	11.5
		Sab.	3.3		
		Myr.	4.5		
		Oth	2.2		
Artocarpus heteroph	33	α-P	0.2	0.45 ± 0.30	44.4
		Sab.	0.15		
		Oth	0.1		
Myrtaceae					
Eucalyptus globulus	37	α-P	1.0	5.0 ± 2.9 1	19.6
		β-P	0.4		
		Lim.	0.3		
		Myr.	0.2		
		Oth	3.2		
Eugenis jambolana	27	NED	NED	NED	NIL
Psidium guajava	36	α-P	0.6	1.8 ± 1.5	33.3
		Sab.	0.8		
		Oth	0.4		

Table 1. *Continued*

Plant Species	Temp. (°C)	Emission	E.R. ($\mu g\ g^{-1}h^{-1}$)	T.E.R. ($\mu g\ g^{-1}h^{-1}$)	α-P (%)
Rutaceae					
Citrus limon	36	α-P	0.6	7.9 ± 2.8	7.6
		β-P	1.1		
		Lim.	3.8		
		Myr.	1.3		
		Oth	1.1		
Citrus sinensis	26	β-P	0.26	1.75 ± 0.57	NIL
		Lim.	0.2		
		Myr.	1.09		
		Oth	0.2		
Murraya koenigii	32	α-P	2.5	3.83 ± 1.6	65.2
		β-P	0.13		
		Lim.	0.5		
		Myr.	0.2		
		Oth	0.5		
Sapotaceae					
Madhuca latifolia	27	Oth	0.3	0.3 ± 0.18	NIL
Manilkara hexandra	25	Oth	1.1	1.1 ± 1	NIL
Mimusops elengi	35	NED	NED	NED	NIL
Sterculiaceae					
Sterculia alata	36	NED	NED	NED	NIL
Sterculia urens	38	NED	NED	NED	NIL

E.R.: emission rate; T.E.R.: total emission rate; α -P: α-pinene; β-P: β-pinene; Lim: limonene; Myr.: myrcene; Sab.: sabinene; Car.: carene; Cam.: camphene; Oth: other; NED: no emission detectable; NIL: no emission

C_T is calculated as follows:

$$C_T = \exp.\{C_{T1}(T - T_s)(R \times T_s \times T)^{-1}\}/0.961 + \exp.\{C_{T2} \times (T - T_m)(R \times T_s \times T)^{-1}\} \quad (3b)$$

where, T is the leaf temperature in Kelvin, R is the gas constant (8.314 J K^{-1} mol^{-1}), T_s is the normalising temperature (K), T_m is an empirical coefficient (315 K), C_{T1} is an empirical coefficient (95 000 J mol^{-1}), and C_{T2} is an empirical coefficient (230 000 J mol^{-1}).

The temperature and light functions account for short–term variations in the emission rate, therefore changes in the standard emission factors can account for inter–specific variation, long–term adaptations such as the plant developmental stage, or even for entirely different ecosystem types (Guenther et al., 1995, Monson et al., 1995; Klinger et al., 1998).

Each plant species area average emission capacity was calculated by multiplying foliar density with total VOC emission rate. Isoprene emission rates of three Haryana plant species (*Acacia catechu*, *Acacia tortilis*, and *Prosopis juliflora*) have not been measured previously by researchers. Emission rates of these species were determined by assigning an emission rate at genus basis using the method by Benjamin et al. (1997). The basic approach of this method is that, within broad qualitative ranges, taxonomic relationships between plant species at the lowest possible level (i.e. genus, then family level) can be used to assign measured emission rates to other species within that level for which no measurements exist.

3. Results and Discussion

3.1. Species emission rates

Monoterpene emission rates were measured from 50 plant species belonging to 15 families. The measured emission rates were normalised to the standard temperature of 30 ˚C using the algorithm developed by Guenther et al. (1993). The mean monoterpene emission rates of plant species varied from undetectable to 16.9 $\mu g\ g^{-1}\ h^{-1}$ (Table 1). Maximum monoterpene emission rate of 16.9 $\mu g\ g^{-1}\ h^{-1}$ observed in the case of *Mangifera indica.* All the 50 plant species screened for the monoterpene emission can be divided into four categories according to the classification system of Guenther et al. (1996) (i) negligible or below detection limit (BDL) monoterpene emitting species (< 0.2 $\mu g\ g^{-1}\ h^{-1}$, n=16), (ii) low emitting species (0.2 to 1 $\mu g\ g^{-1}\ h^{-1}$, n=12), (iii) moderate emitting species (1 to 3 $\mu g\ g^{-1}\ h^{-1}$, n=17), and (iv) high emitting species (> 3 $\mu g\ g^{-1}\ h^{-1}$, n=5). Thirty two percent of the species were negligible emitters and 68% were emitters of monoterpene.

A large inter species variations in monoterpene emission rates were observed (Table 1), mainly on account of a combination of various factors such as genetic makeup (Monson et al., 1994), physiological variations, leaf age (Monson et al., 1994; Steinbrecher et al., 1997), variations in plants leaf morphological and anatomical features (Lerdou et al., 1994). Leaves of different plant species vary in terms of presence or absence of resin ducts, resin blisters, leaf storage cavities, trichomes, and oil glands. Plant species leaf possessing any of these structures have tendency to emit relatively large amounts of monoterpenes.

Seven monoterpenes namely, *α*–pinene, *β*–pinene, *d*–limonene, myrcene, sabinene, camphene, and carene were identified in the emission samples. Some other monoterpenes present in the emission samples could not be identified. These monoterpene emission rates were estimated using *α*–pinene standard and given in Table 1 under a separate category, "other". The analysis of data given in Table 1 shows that 14% plant species emitted *α*–pinene, 16% *β*–pinene, 10% *d*–limonene, 10% myrcene, 12% sabinene, 3% camphene, 3% carene, and 32% "other" monoterpenes, which could not be identified in the samples. Geron et al. (2000) have also reported the following monoterpene emission pattern for the deciduous forest ecosystem of US: *α*–

pinene (20–40%), *β*–pinene (10–20%), *d*–limonene (5–20%), myrcene (0–5%), sabinene (10–25%), phellandrene (5–10%), and *γ*–terpinene (0–5%), which is comparable to the emission pattern of plant species examined in the present study. An attempt has been made to compare results of this study with the literature data. Out of 50 plant species, only 6 plant species have been investigated earlier. It can be seen from Table 2 that there is a reasonable agreement between the present study and literature. The small differences between observed and reported emission rates could be due to differences in sampling methods, season, leaf age, and exposure to different levels of air pollution. Previous studies have reported that leaf age, season and air pollution influence monoterpene emissions (Juuti et al., 1990; Monson et al., 1994; Singh et al., 2008).

Table 2. *A comparison of present study monoterpene emission rates (μg g^{-1} h^{-1}) with the literature data*

Scientific name	Present study	Literature values	Reference
Acacia farnesiana	nil	nil	Klinger et al., 2002
Cinnamomum camphora	0.03	0.03	Corchnoy et al., 1992
Citrus limon	7.9	3.2	Winer et al., 1989
Citrus sinensis	1.75	1.8	Winer et al.,1992
Eucalyptus globulus	5.0	9.2	Evans et al., 1982
Ficus elastica	0.35	0.5	Cronn and Nutmagul, 1982

3.2. VOC emission from the forest of Haryana state

Forest of Haryana state consists of about 80% plantation and 20% natural forest (Sapra, 2000), which is dominated by a few broad leaf deciduous species (Table 3). VOC emission capacity of forest of Haryana state was estimated using the method by Guenther et al. (1995) and it was found to be 20.96 mg C m^{-2} h^{-1} (Table 3). Area averaged VOC emission capacity for individual plant species ranged from 0.04 to 12.1 mg C m^{-2} h^{-1}. Isoprene and monoterpene emissions constituted 83.6 and 16.4% of the total VOC emissions, respectively. About 52.9% of the plant species were found to be high emitters (≥ 10 μg g^{-1} h^{-1}) of VOC. Some of the high VOC emitting plant species such as *Eucalyptus globulus, Mangifera indica, Dalbergia sisoo* and *Populus* species have been raised in the Haryana forest under various intensive planting schemes implemented by the government of India. These four plant species comprise 38.8% of total forest area and account 87.69% of total VOC emissions (Table 3). It is difficult to compare directly our estimate with other available estimates for tropical regions because forest of Haryana mainly is a plantation forest dominated by a few high VOC emitting plant species. Nevertheless, an attempt has been made to compare our estimate with other estimates for tropical forests. We found that our estimated values are about 2.4 times higher than those reported in the literature (Table 4). It has been reported that landscapes dominated by plantation species emit VOCs on an average 3 times higher than natural landscapes (Geron et al., 2006). The differences in the values could be on account of following factors such as variations in climatic regimes, plant species compositions, successional stage

Table 3. *Area averaged VOC emission capacity of plant species of Haryana forest*

Plant Species	Cover (%)	F.D.	Isoprene [a]	Monoterpene	TER	AA EC
Azadirachta indica	3.4	49.3	BDL	2.4	2.4	0.04
Mangifera indica	2.4	60.0	20.9	16.9	37.9	0.65
Zizyphus jujuba	1.9	7.6	BDL	4.2	4.2	0.06
Dalbergia sissoo	12.1	290.4	63.4	BDL	63.4	12.1
Eucalyptus globulus	21.8	153.6	43.2	5.1	48.3	5.1
Morus alba	2.2	7.9	16.8	11.3	28.1	0.22
Eugenia jambolanum	1.1	27.5	17.2	BDL	17.2	0.17
Populus species	2.5	10.5	39.6	BDL	39.6	0.53
Prosopis juliflora	15.1	162.3	3.8	1.5	5.3	0.82
Acacia species	24.5	131.4	BDL	BDL	BDL	0.03
Miscellaneous species						
Ficus species			45.6	1.6	47.2	
Pongamia pinnata			25.7	2.32	28.0	
Salmalia malabarica			3.3	2.9	6.2	
Albizzia lebbeck			0.5	2.15	2.5	
Terminalia arjuna			BDL	0.08	0.08	
Pithecellobium dulce			16.7	0.47	17.2	
Kigelia pinnata			0.8	1.26	2.0	
Sub total	7.2	180.2	13.2	1.54	14.7	1.24
Total			218.1	42.94	261.1	20.96

F.D.: Foliar density (in g m^{-2}); TER: Total VOC emission rate (μg C g^{-1} h^{-1}); AAEC: Area average emission capacity (in mg C m^{-2} h^{-1}).

Species designated as below detection limit (BDL) in table are assigned an emission value of 0.20 μg Cg^{-1} h^{-1}.

Normalised isoprene and monoterpene emission rate values (in μg Cg^{-1} h^{-1}) are mentioned in table

[a] *Isoprene emission rates reported by Singh et al. (2008).*

of plant species, base emission factors and foliar densities of the landscapes compared for emission capacity. Contrary to the natural landscapes of central Africa, Kalahari woodland and savannas of South Africa, forest of Haryana is a predominantly plantation forest, dominated by early succesional plant species (Sapra, 2000). One study has reported that early successional plant species emit more VOC emission than late successional plant species (Klinger et al., 2002). Two plant species of Haryana forest namely, *Dalbergia sisoo* and *Eucalyptus globulus,* which constitute about 34% of forest area, were found to account about 82% of total VOC emissions (Table 3). Whereas, Kalahari and central Africa landscapes dominant plant species reported as negligible emitters of VOCs (Guenther et al., 1996; Otter et al., 2002). Nevertheless, our estimate suffers from uncertainties due to various factors and can be further improved by accurate measurements of vegetation cover distribution and foliar density (leaf area index and leafy biomass) of individual plant species. In addition, effects of leaf age, seasons, and air pollution on base emission factors may also be incorporated to improve the accuracy of the estimates.

Table 4. *Comparison of our estimate and other VOC emission estimates*

Landscape	Site	VOC Emission Capacity (mg C m^{-2} h^{-1})	Reference
Natural Kalahari woodland	Zambia	8.3	Otter et al., 2002
Savannas	Ntoma, SA	8.76	Guenther et al., 1996
Haryana forest	Haryana, India	20.96	This study

4. Conclusions

In this study, 50 Indian plant species were examined for monoterpene emissions using a dynamic enclosure system. Out of the 50 plant species, 32% were negligible emitters, and 68% were monoterpene emitters. In India numerous plantation programmes have been implemented in order to meet ever growing demand for forest products and to improve the quality of environment. As a result, waste land, agricultural and mountainous regions are being converted to tree plantations. The pace of planting tree species are expected to increase in the future in view of national goal of achieving 33% forest cover from the existing 20.6%. Therefore, biogenic VOC emission fluxes to atmosphere may increase, which could have serious impact on regional and global VOC budget. Moreover, increased VOC emissions could have profound impact on regional ozone and aerosol chemistry. This study shows that change in landscape significantly alters VOC emission pattern. Forest of Haryana state is found to emit about 2.4 times more VOC than those reported in literature for some tropical forests.

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References

Anon, 1999. National Forestry Action Programme. Report of Ministry of Environment and Forest, Government of India, New Delhi.

Atkinson, R., 2000. Atmospheric chemistry of VOCs and NOx. *Atmospheric Environment* 34, 2063-2101.

Benjamin, M.T., Sudol, M., Vorsatz, D., Winer, A.M., 1997. A spatially and temporally resolved biogenic hydrocarbon emission inventory for the California South Coast Air Basin. *Atmospheric Environment* 31, 3087-3100.

Corchnoy, S.B., Arey, J., Atkinson, R., 1992. Hydrocarbon emissions from twelve urban shade trees of the Los Angeles, California, air basin. *Atmospheric Environment* 26, 339-348.

Cronn, D.R., Nutmagul, W., 1982. Analysis of atmospheric hydrocarbons during winter MONEX. *Tellus* 34, 159-165.

Evans, R.C., Tingey, D.T., Gumpertz, M.L., Burns, W.F., 1982. Estimates of isoprene and monoterpene emission rates in plants. *Botanical Gazette* 143, 304-310.

Fehsenfeld, F., Calvert, J., Fall, R., Goldan, P., Guenther, A.B., Hewitt, C.N., Lamb, B., Liu, S., Trainer, M., Westberg, H., Zimmerman, P., 1992. Emissions of volatile organic compounds from vegetation and the implications for atmospheric chemistry. *Global Biogeochemical Cycles* 6, 389-430.

Geron, C., Owen, S., Guenther, A., Greenberg, J., Rasmussen, R., Bai, J.H., Li, Q.J., Baker, B., 2006. Volatile organic compounds from vegetation in southern Yunnan Province, China: emission rates and some potential regional implications. *Atmospheric Environment* 40, 1759-1773.

Geron, C., Rasmussen, R., Arnts, R.R., Guenther, A., 2000. A review and synthesis of monoterpene speciation from forests in the United States. *Atmospheric Environment* 34, 1761-1781.

Guenther, A., Otter, L., Zimmerman, P., Greenberg, J., Scholes, R., Scholes, M., 1996. Biogenic hydrocarbon emissions from southern African savannas. *Journal Geophysical Research-Atmospheres* 101, 25859-25865.

Guenther, A., Hewitt, C.N., Erickson, D., Fall, R., Geron, C., Graedel, T., Harley, P., Klinger, L., Lerdau, M., Mckay, W.A., Pierce, T., Scholes, B., Steinbrecher, R., Tallamraju, R., Taylor, J., Zimmerman, P., 1995. A global model of natural volatile organic compound emissions. *Journal of Geophysical Research-Atmospheres* 100, 8873-8892.

Guenther, A.B., Zimmerman, P.R., Harley, P.C., Monson, R.K., Fall, R., 1993 Isoprene and monoterpene emission rate variability: model evaluations and sensitivity analyses. *Journal of Geophysical Research-Atmospheres* 98, 12609-12617.

Juuti, S., Arey, J., Atkinson, R., 1990. Monoterpene emission rate measurements from a Monterey pine. *Journal of Geophysical Research* 95, 7515-7519.

Klinger, L.F., Li, Q.J., Guenther, A.B., Greenberg, J.P., Baker, B., Bai, J.H., 2002. Assessment of volatile organic compound emissions from ecosystems of China. *Journal of Geophysical Research-Atmospheres* 107, art. no. 4603.

Klinger, L., Greenberg, J., Guenther, A., Zimmerman, P., Bangui, M., Mutsambote, J.M., Kenfack, D., 1998. Patterns in volatile organic compound emissions along a savanna-rainforest gradient in Central Africa. *Journal of Geophysical Research-Atmospheres* 102**,** 1443-1454.

Lerdau, M., Dilts, S.B., Westberg, H., Lamb, B.K., Allwine, E.J., 1994. Monoterpene emission from ponderosa pine. *Journal of Geophysical Research* 99, 16609-16615.

Monson, R.K., Lerdau, M.T., Sharkey, T.D., Schimel, D.S., Fall, R., 1995. Biological aspects of constructing volatile organic compound emission inventories. *Atmospheric Environment* 29, 2989-3002.

Monson, R.K., Harley, P.C., Litvak, M.E., Wildermuth, M., Guenther, A.B., Zimmerman, P.R., Fall, R., 1994. Environmental and developmental controls over the seasonal pattern of isoprene emission from aspen leaves. *Oecologia* 99, 260-270.

Otter, L.B., Guenther, A., Greenberg, J., 2002. Seasonal and spatial variations in biogenic hydrocarbon emissions from southern African savannas and woodlands. *Atmospheric Environment* 36, 4265-4275.

Padhy, P.K., Varshney, C.K., 2005. Isoprene emission from tropical tree species. *Environmental Pollution* 135, 101-109.

Sapra, R., 2000. Tree cover of Haryana. *Indian Forester* 814-821.

SFR, 2005. State of Forest Report. Ministry of Environment and Forest, Government of India, New Delhi.

Singh, R., Singh, A.P., Singh, M.P., Kumar, A., Varshney, C.K., 2008. Emission of isoprene from common Indian plant species and its implications for regional air quality. *Environmental Monitoring and Assessment* 144, 43-51.

Singh, A.P., Varshney, C.K., Singh, U.K., 2007. Seasonal variations in isoprene emission from tropical deciduous tree species. *Environmental Monitoring and Assessment* 131, 231-235.

Steinbrecher, R., Hauf, K., Rabong, R, Steinbrecher, J., 1997. Isoprenoid emission of oak species typical for the Mediterranean area: source strength and controlling variables. *Atmospheric Environment* 31, 79-88.

Street, R.A., Duckham, S.C., Hewitt, C.N., 1996. Laboratory and field studies of biogenic volatile organic compound emissions from Sitka spruce (*Picea sitchensis* Bong.) in the United Kingdom. *Journal of Geophysical Research-Atmospheres* 101, 22799-22806.

Varshney, C.K., Singh, A.P., 2003. Isoprene emission from Indian trees. *Journal of Geophysical Research-Atmospheres* 108, art. no. 4803.

Winer, A.M., Arey, J., Atkinson, R., Aschmann, S.M., Long, W.D., Morrison, L.C., Olszyk, D.M., 1992. Emission rates of organics from vegetation in California's central valley. *Atmospheric Environment Part A-General Topics* 26, 2647–2659.

Winer, A.M., Arey, J., Aschmann, S.M., Atkinson, R., Long, W.D., Morrison, L.C., Olszyk, D.M., 1989. Hydrocarbon Emission From Vegetation Found in California's Central Valley. In: Final Report, California Air Resource Board Contract No A732-155, Nov., Riverside, USA, 328 pp.